Indicate what value should be provided instead of ??? in line 6 to minimize space, and how it should depend on myrank.

Solution: myrank == 0 ? (size * numProcs) : 0
Organization of a Distributed-Memory Multiprocessor (Recap)

Figure (a)
- Host node ($P_c$) connected to a cluster of processor nodes ($P_0 \ldots P_m$)
- Processors $P_0 \ldots P_m$ communicate via an interconnection network which could be standard TCP/IP (e.g., for Map-Reduce) or specialized for high performance communication (e.g., for scientific computing)

Figure (b)
- Each processor node consists of a processor, memory, and a Network Interface Card (NIC) connected to a router node (R) in the interconnect

In MPI, processes communicate by sending messages to each other. Distributed Map-Reduce offers an alternative approach for programming distributed-memory multiprocessors.
MapReduce Pattern (Recap from Lecture 8)

- Apply **Map** function $f$ to user supplied record of key-value pairs
- Compute set of intermediate key/value pairs
- Apply **Reduce** operation $g$ to all values that share same key to combine derived data properly
  — Often produces smaller set of values
- User supplies Map and Reduce operations in functional model so that the system can parallelize them, and also re-execute them for fault tolerance
- Distributed Map-Reduce frameworks (Hadoop, Spark) support the Map-Reduce pattern (with extensions) on a distributed-memory multiprocessor
Distributed MapReduce Execution

Fine granularity tasks: many more map tasks than machines

Bucket sort to get same keys together

E.g. 2000 servers => ≈ 200,000 Map Tasks, ≈ 5,000 Reduce tasks
Apache Hadoop Project

- Hadoop: an open-source software framework that supports data-intensive distributed applications, licensed under the Apache v2 license.

- Goals / Requirements:
  - Abstract and facilitate the storage and processing of large and/or rapidly growing data sets
  - Simple programming models
  - High scalability and availability
  - Fault-tolerance
  - Move computation rather than data

- Distributed design, with some centralization
  - Main nodes of cluster are where most of the computational power and storage of the system lies
  - Main nodes run TaskTracker to accept and reply to MapReduce tasks, and also DataNode to store needed blocks closely as possible
  - Central control node runs NameNode to keep track of HDFS directories & files, and JobTracker to dispatch compute tasks to TaskTracker

- Written in Java, also supports Python and Ruby

- Acknowledgment: slides on Hadoop from UCI CS 237 course by Nalini Venkatasubramanian
Hadoop’s Architecture

- **NN** = Name Node
- **DN** = Data Node
- **TT** = Task Tracker

Acknowledgment: slides on Hadoop from UCI CS 237 course by Nalini Venkatasubramanian
Spark and Iterative Map/Reduce

- Apache Spark: General purpose functional programming over a cluster
  - Caches results of map/reduce operations in memory so they can be used on subsequent iterations
  - Tends to be 10-100 times faster than Hadoop for many applications
Apache Spark Project

- Spark is a data parallel processing framework, which means it will execute tasks as close to where the data lives as possible (i.e. minimize data transfer).
- Spark follows a paradigm of keeping as much data in-memory and spilling excess to disk rather than pulling data from disk when needed.
- Spark decomposes your program into tasks and handles dispatching and scheduling of these tasks on worker nodes in your cluster.
- Spark revolves around the concept of a resilient distributed datasets (RDD).
The key construct in Spark is the Resilient Distributed Dataset (RDD)

- RDDs can be though of as a collection of key-value pairs

An RDD is a giant immutable collection, distributed in a redundant way over all the machines in a cluster

The types of the elements in the RDD can be arbitrary elements

If the elements are pairs, then the RDD acts like a table

Computations on an RDD (including Map/Reduce) can be expressed as functional programming operations
Working with RDDs

- There are two kinds of operations one can perform over an RDD.
  - **Transformations**: Operations like `map`, `filter`, `join` etc. that just return another RDD. They are *lazy* operations.
  - **Actions**: These are operations that *actually produce* results like `count`, `collect`, `save` etc. These operations don't return an RDD.
  - Similar to *intermediate* and *terminal* operations in Java 8 Streams.
Advantages of Immutability

• The distributed nature of RDDs is not evident in the programming model.
• RDD elements can be replicated for fault tolerance.
• Purely functional operations can be easily defined on RDDs.
• Because RDDs are immutable, all the operations from purely functional programming can be applied and parallelized in a straightforward way.
• The runtime has great flexibility in scheduling operations on RDDs and executing them in parallel on partitions.
• Partitions of RDDs can be recomputed from their lineage.
JavaRDD<String> file = context.textFile(inputFile);

JavaPairRDD<String, Integer> counter =
    file.flatMap(s -> Arrays.asList(s.split(" "))).
        mapToPair(s -> new Tuple2<>(s, 1)).
            reduceByKey((a, b) -> a + b);

counter.collect().forEach(System.out::println);

// Definition of “flatMap”
// x.flatMap(f) = x.map(f).flatten()

// Definition of “reduceByKey”
// x.reduceByKey(f) = x.groupByKey()
//    .map(xs -> xs.reduce(f))
["this is a line",
"this is another line",
"this is yet another line"]
.map(s -> Arrays.asList(s.split(" ")))
.flatten()
-->
[["this", "is", "a", "line"],
 ["this", "is", "another", "line"],
 ["this", "is", "yet", "another", "line"]
.flatten()
-->
["this", "is", "a", "line", "this", "is", "another", "line", "this", "is", "yet", "another", "line"]
Word Count in Apache Spark

["this", "is", "a", "line", "this", "is", "another", "line", "this", "is", "yet", "another", "line"]

.map(s -> new Tuple2<>(s, 1))

-->[["this",1], ["is",1], ["a",1], ["line",1], ["this",1], ["is",1], ["another",1], ["line",1], ["this",1], ["is",1], ["yet",1], ["another",1], ["line",1]]
Word Count in Apache Spark

[["this",1], ["is",1], ["a",1], ["line",1],
 ["this",1], ["is",1], ["another",1],
 ["line",1], ["this",1], ["is",1],
 ["yet",1], ["another",1], ["line",1]]
.groupByKey().map(xs -> xs.reduce(
    (a,b) -> a + b))

___>
[["this", [1,1,1]],
 ["is", [1,1,1]],
 ["a", [1]],
 ["line", [1,1,1]],
 ["another", [1,1]],
 ["yet", [1]]].map(xs -> xs.reduce((a,b) -> a + b))
Word Count in Apache Spark

[["this", [1,1,1]],
 ["is", [1,1,1]],
 ["a", [1]],
 ["line", [1,1,1]],
 ["another", [1,1]],
 ["yet", [1]].map(xs -> xs.reduce(
   (a,b) -> a + b)
) —>

[["this", [1,1,1]].reduce((a,b) -> a + b),
 ["is", [1,1,1]].reduce((a,b) -> a + b),
 ["a", [1]].reduce((a,b) -> a + b),
 ["line", [1,1,1]].reduce((a,b) -> a + b),
 ["another", [1,1]].reduce((a,b) -> a + b),
 ["yet", [1]].reduce((a,b) -> a + b))]

COMP 322, Spring 2018 (M. Joyner, Z. Budimlić)
Word Count in Apache Spark

```scala
[["this", [1,1,1]].reduce((a,b) -> a + b),
 ["is", [1,1,1]].reduce((a,b) -> a + b),
 ["a", [1]].reduce((a,b) -> a + b),
 ["line", [1,1,1]].reduce((a,b) -> a + b),
 ["another", [1,1]].reduce((a,b) -> a + b),
 ["yet", [1]].reduce((a,b) -> a + b))]

--> 

[["this", 3], ["is", 3], ["a", 1],
 ["line", 3], ["another", 2], ["yet", 1]]
```